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AN EVALUATION OF FLASHTUBE SIGNAL CHARACTERISTICS

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FINAL REPORT

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·tract

"nited States Coast Guard has long been interested in using flashtubes as ·to-navigation. They are highly conspicuous and are energy efficient. In . . .ingle flick operation mode, mariners report difficulty in fixing the exact location of the flashtube, presumably due to the extremely short "on" time (less than 10 milliseconds). This factorial experiment investigated the effect on observer performance as each of three factors was varied: (1) Flash Repetition Rate; (2) Flick Frequency; and (3) Number of Flicks comprising the multiflick flash. An analysis of variance revealed all three main factors to be significant as well as some interactions. From the model provided, observer performance can be predicted by specifying the three factors. A simplifying parameter is introduced which reduces the performance model to two factors. Recommendations are made for each of these factors.

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METRIC CONVERSION FACTORS

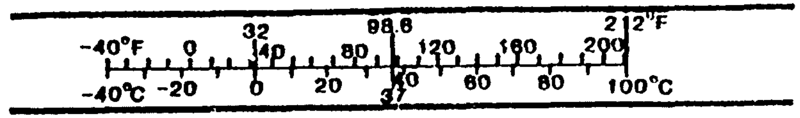
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (WEIGHT)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (EXACT)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures. Price $2.25. SD Catalog No. C13.10.286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (WEIGHT)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.125	cups	c
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (EXACT)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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I would like to thank Lieutenant Daniel SMITH and the participating cadets of ECHO Company as well as Lieutenant Peter SEIDLER and the participating cadets of BRAVO Company, United States Coast Guard Academy. Their highly motivated volunteer efforts and cooperation made this experiment possible.

I would also like to thank Lieutenant Patrick FLANAGAN, Mathematics Department, United States Coast Guard Academy, for his assistance in analyzing the data.

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Finally, to my wife and family, a special note of appreciation for their loving support.

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I. INTRODUCTION

A. Coast Guard Interest In Flashtubes

The United States Coast Guard has been interested in the flashtube as an aid to navigation for almost 20 years. They offer a highly intense, brief burst of light which can be detected over great maritime distances. Flashtubes offer the additional benefit of low energy consumption in the single flick mode. The combination of high detectability and low energy consumption is highly desirable in an aid to navigation. The flashtube, however, suffers from three serious shortcomings. First, the brief burst of light is so short in duration that the mariner cannot fix its location in his visual field. Second, the mariner has difficulty judging distance to the flashtube. This depth perception problem has been reported by many mariners. Finally, the burst of light is so intense that mariners relatively close to the light when it flashes usually suffer temporary degradation of night vision. This familiar phenomenon has been labelled "the flashbulb effect". These shortcomings have eroded much support for flashtubes from the maritime community. A satisfactory flashtube aid to navigation should minimize these shortcomings while attempting to maximize the benefits.

The Coast Guard Office of Research and Development in conjunction with the Office of Navigation determined there was a need to better understand the factors that influence how well (or how poorly) a flashtube signal is perceived. On the premise that longer flash "on" times would help correct some of the shortcomings of the flashtube visual signal, 42 multiflick flashtube signals were devised and tested for observer performance. The results of this investigation are intended to address the problem of the inability of the mariner to maintain the flash location in his visual field.

B. What is a Flashtube?

A flashtube is designed to provide a high intensity flash of very brief duration. It is typically constructed of a glass envelope filled with xenon gas below atmospheric pressure and containing two main electrodes at either end. External to the envelope is a wire electrode wound around the envelope. The glass tube acts as an open circuit with voltage applied to the main electrodes. A trigger pulse is applied to the external electrode which induces ionization of the xenon gas within the envelope, allowing it to conduct. The main electrodes then discharge in a brilliant arc through the highly luminescent conductive gas. This is a fairly efficient process. The typical flashtube converts nearly 35% of the input energy to light (IES, 1981). There are three primary circuits in a flashtube:

(1) The discharge circuit, through which it is possible to vary both the flash duration and the light output.

(2) The charge circuit, which stores energy in a capacitor bank.

(3) The trigger circuit, which provides the high voltage ionizing trigger pulse.

Figure 1 is a simple schematic of this arrangement (IES, 1981).

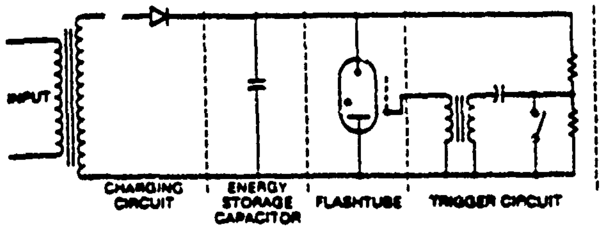

FIGURE 1: A SIMPLE SCHEMATIC OF FLASHTUBE CIRCUITRY.

C. Psychophysics and Human Visual Perception

Psychophysics is defined as, "...a branch of psychology that studies the effect of the physical processes upon the mental processes of an organism." (Webster's, 1972). This investigation may then be termed a psychophysical experiment involving the physical flashing light stimulus and how it is perceived by the observer. Perception, including visual perception, is not easily quantifiable. Conspicuity, which is defined as the property of "attracting attention", or of being "obvious to the mind or eye" (Webster's, 1972), is one such area. One would like to arrive at some sort of scale to relate the mental process of distinguishing the most attractive of several simultaneous visual signals to the physical stimulus itself. With such a scale, one could determine conspicuity merely by measuring the physical stimulus. This has not been accomplished as yet. Sensation, as defined by the International Dictionary of Aids to Marine Navigation (International, 1970) is an "Element...which cannot be analyzed further." Although we can't measure the actual sensation, we can measure the performance associated with that sensation.

The approach in this investigation has been to obtain empirical evidence that can be used to recommend signal components making up the composite flashtube signal, such as flash rate and flick frequency. As designed, the experimental technique might be classified as a "reaction time" investigation. The criticism that such a technique measures the difficulty of the response rather than the value of the signal is allayed by the facts that: (1) each signal is equally subjected to the same experimental techniques, (2) we are measuring relative performances, and (3) the experimental technique duplicates a real-world event (i.e., mariners routinely require bearings to flashing lights). A detailed discussion of the human visual system and visual perception is not suitable here. However, some relevant findings are presented here to provide background and to acquaint the reader with various considerations on this topic:

(1) The Critical Flicker Frequency (CFF, see page 4) depends on several factors, especially the illuminance of the source, (Graham, 1965). The higher the source illumination, the higher CFF. "This is a substantial effect: for every tenfold increase in stimulus intensity there is a 10 to 15 Hertz increase in CFF until very high intensities are reached, where CFF stabilizes for larger flashes somewhere above 60 Hertz", (Boynton, 1979).

(2) When several flashes are presented at threshold within a brief period known as the critical duration, they appear as a single flash and at threshold, the multiple flashes require the same total energy whether delivered in one or five pulses, (Davy, 1952). Stated simply, detection threshold is that level of luminance to which a dark adapted observer responds positively to the stimulus at some specified level (e.g., the observer responds, "Yes, I see the light", fifty percent of the time).

(3) The threshold critical duration is approximately 0.10 seconds for the dark adapted eye. Up to critical duration the threshold intensity decreases proportionally according to Bloch's Law:

$$It = \text{constant}$$

Beyond critical duration (long flashes) there is a constant requirement for intensity to produce a threshold response. "...as the duration of the light increases, up to a certain critical duration, the intensity required to produce a threshold response decreases proportionally. Hence the product of intensity and duration remains constant", (Long, 1951). Perhaps it is easier to consider the eye as a detector where a certain quanta of energy is required to evoke a positive response. Apparently, below critical duration it isn't important how the energy arrives (neither the distribution of a single pulse nor multiple pulses) but that some threshold energy does arrive to evoke the response.

(4) Below critical duration the particular shape of the waveform has no effect on the total energy required for a threshold response (Long, 1951).

(5) At frequencies above fusion, brightness is proportional to time-average luminance (Talbot Plateau Law) (Graham, 1965). Above fusion (where individual flicks cannot be distinguished), the flickering light will have the same brightness as a steady light of the same time-averaged luminance.

(6) As you increase duty cycle (light-time fraction of the signal period) the CFF shows a continuous decrease, holding average luminance constant, (Graham, 1965).

D. Definitions

The following definitions apply throughout this paper.

FLASH: A continuous burst of light having a precise beginning and an abrupt halt.

SINGLE FLICK FLASH: A flashtube permitted to discharge (flick) only once; the total "on" time of such a flash can be on the order of microseconds. In this investigation, the "on" time was approximately 10 milliseconds.

FLICK FREQUENCY: In Hertz, the number of times per second the flashtube is permitted to discharge. A flashtube operating at 10 HZ would discharge ten times per second.

MULTIFLICK FLASH: A continuous burst of light composed of several flicks in rapid succession (depending on the flick frequency). The frequency of flicks is so high, the observer cannot distinguish individual flicks but perceives only a single uninterrupted flash. This includes those flick frequencies where the flash appears to ripple.

CRITICAL FLICKER FREQUENCY: That flick frequency wherein the observer can no longer distinguish a flicker. The source appears as an uninterrupted flash.

FLASH REPETITION RATE: The number of times a source flashes in a specified time period. The flash may be a single flick flash or it may be a multiflick (or composite) flash. Conventionally, this is often expressed as 1 flash per specified time period. This is actually a misnomer. Here, a higher repetition rate is one that flashes less often. A 4-second flash repetition rate (i.e. one flash every four seconds) is said to be higher than a 1-second flash repetition rate. In this investigation, the three flash rates were:

(1) one flash every second (FRR = 1)
(2) one flash every two seconds (FRR = 2)
(3) one flash every four seconds (FRR = 4)

NUMBER OF FLICKS (N): The number of flicks comprising a multiflick flash. In this experiment, there were seven flick combinations: 1, 3, 5, 8, 16, 32, 64.

LOCK ON: The observer knows with reasonable certainty the location of (or bearing to) a flashing source.

VISUAL FIELD: The observer's unobstructed panorama.

DUTY CYCLE: From the onset of the initial flash to the onset of a subsequent flash (or subsequent group of flashes) in a periodically flashing light may be described as the period of the flash repetition rate. The duty cycle is the ratio of light "on" time to total period of the signal. For example, a source that flashes once every 4.0 seconds and has a flash "on" time of 0.4 seconds will have a duty cycle of 0.1. Changing the flash repetition rate, the flick frequency or the number of flicks comprising the multiflick flash will consequently change the duty cycle.

E. Statement of the Problem

Flashtubes operating in the single flick mode produce a brilliant but very brief (less than 10 millisecond) flick. This flick is so brief in duration that many mariners cannot maintain the flash location in their visual field. From one flash to the next, the flashtube source will appear to "jump" from one distinct location to another distinct location in the observer's

field of view. Mariners also report inability to accurately assess the distance to the flashtube source. This depth perception information is important to make full use of the aid to navigation. Finally, mariners close aboard to a flashtube when it flashes are temporarily "blinded" by the brilliant flash. This effect is known as the "flashbulb effect".

It would appear that lengthening the flashtube "on" time for each flash could limit the "jump" phenomenon. However, what should the proper flash duration be? How many flicks are optimum to construct a multiflick flash? What flick frequency is optimum? How does flash rate affect signal performance?

F. Goals

The Statement of the Problem, Section E., contains several unanswered questions. The general goals of this investigation are to answer those questions so that an optimum flashtube signal characteristic can be obtained or at least recommendations can be made concerning the composition of the flash signal. Specifically:

(1) State the optimum flash rate for the signal.
(2) State the optimum flick frequency to employ.
(3) State the optimum number of flicks comprising the composite flash.

II. METHODOLOGY

A. Brief Overview of Experimental Set Up

As indicated earlier, perceptual judgements are often highly subjective. For example, imagine two observers standing side by side in an immense, empty, totally dark auditorium. There are no visual cues. There are no audio cues. Suddenly, they are presented with a brief flash of light. It should be apparent that it will be extremely difficult for them to communicate to each other the precise location of the flash, since their coordinate systems are not identical. Eventually, they may come to an agreement on the general location of the flash. But if we were trying to determine which of several flashes evoked the "best" perception (however we define "best"), we must have a measure of the observer's perception. The scenario just described is too subjective. A more objective means is needed; one that marries some type of observer performance to the actual "performance" of the signal so that the best observer performance would relate to the best signal.

I therefore chose to quantify the observer's performance by requiring him to observe a flashing light source and then take a bearing on that source using a marine alidade. This method, incidentally, has been employed similarly by others (White, 1965, and Walraven, 1975). The amount of time required to obtain the bearing (lock on) and the accuracy of that bearing would provide the performance data. Those signals for which performance was statistically better must be "better" signals.

The experiment, performed in the Research and Development Center's 50-meter light tunnel (4m X 50m), was conducted as follows: The naive observer was led into the totally darkened chamber and seated on an observation platform containing the marine alidade. He had no knowledge of room dimension or signal source direction. A small light inside the alidade was turned on to illuminate the crosshair. This light level was low enough so as not to illuminate the observation area. The observer was permitted to dark adapt for approximately fifteen minutes. The suprathreshold flashing light source was located approximately 40m distant. The rotating platform was programmed to rotate very slowly (about 4 degrees per minute) in a 20 degree arc on either side of the axis from source to platform (see Figure 2).

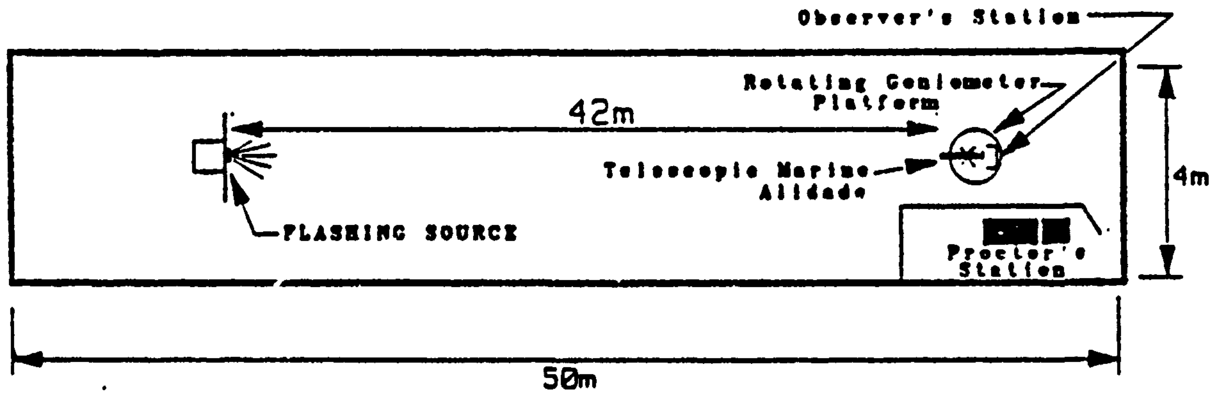

FIGURE 2: VIEW OF OBSERVATION CHAMBER FROM ABOVE

The observer was placed in motion and told to prepare to take a bearing to the flashing light. The flashing source was turned on and the observer's elapsed lock-on time was recorded, as well as the accuracy of the bearing he took. Including practice runs and dark adaptation time, each observer took about 1-1/2 hours to complete the observations. Each observer was presented with 42 different flashtube signals in a random fashion. The observer was permitted only one observation of each of the 42 signals. Three flash rates were represented: 1 second, 2 second, and 4 second. There were seven categories for the number of flicks composing the multiflick flash: N=1, 3, 5, 8, 16, 32, 64. Additionally, two different flick frequencies were also represented: 10 HZ (below CFF) and 44 HZ (above CFF). The 3 flash rates, 2 flick frequencies and 7 flick combinations account for the 42 signals that were presented to the observers.

The Critical Flicker Frequency, which may be treated as a flicker threshold, varies considerably with the luminance of the flickering light. This flicker threshold is low for low luminance levels and higher for high levels of luminance. A high luminance flickering light may fuse (no flicker distinguished) at 50 HZ while a dim source may reach fusion at 15 HZ.

B. Equipment

1. HICON Stroboscope

This device, manufactured for the Coast Guard over 10 years ago, was designed to create multiflick strobe flashes at frequencies between approximately 1 and 80 HZ. The number of flicks emitted, their frequency, and an overall flash rate is selectable. A Hewlett-Packard model 5327A Timer Counter in conjunction with a Wavetek frequency generator was used to insure correct frequency application.

2. Observer's Platform

The observer's platform, constructed of 1/4-inch steel plate was mounted on a Scientific Atlanta Series 5300 Positioner (goniometer). This goniometer is capable of programmable rotation about both vertical and horizontal axes and is accurate to within 0.03 degrees. The movement of the goniometer was controlled in the software written to monitor/control the experiment in the correct manner. A 1942 vintage U.S. Navy Mark II, Mod 0 marine alidade was attached to the platform via an electronic shaft position encoder (72000 counts per revolution). The shaft position encoder output, accurate to 0.01 degrees, was received by the HP9816 desktop computer located at the proctor's station. On completion of an observation, the computer automatically recorded the elapsed time (to within 0.1 seconds) and the angular position of both the alidade and the goniometer.

3. Light Sources

The strobe source, capable of three output levels, was set at the middle output level. A fiber optic probe was placed in front of the strobe lamp and light sealed. The fiber optic cable with a 2.0mm diameter window was then placed approximately 42 meters from the observer. This intense point source provided a suprathreshold signal. In the Pilot Study, the incandescent source was a standard aids to navigation, 2.03A lamp (12 VDC). It, too, was connected to a fiber optic cable with a 5.0mm window and placed approximately two inches vertically over the strobe cable window.

C. Subjects

Twenty-six volunteer subjects (19 male, 7 female) were chosen for the experiment. All subjects were United States Coast Guard Academy cadets. Most had little or no experience in using the marine alidade. The average observer age was 20 years. The average visual distance acuity for both eyes was 20/18. As a group, the subjects seemed highly motivated.

D. Instructions to Subjects

"The purpose of this experiment is to determine how well you perform when presented with several different types of light signals. Your performance will be measured by how long it takes you to lock on to the target as well as how accurate your bearing is. I am primarily interested in the accuracy of your bearing but please remember that we are trying to simulate a shipboard scenario here, so the amount of time you take should be as little as possible to arrive at what you feel is an accurate bearing.

"In a moment, I will escort you into the darkened observation room, where you will be seated on the observation platform behind the alidade. I will again explain the steps you are to follow while your eyes become adapted to the dark.

"On the command 'Standby to mark', you will begin to search for the light source. When it comes on, it will be bright enough so as to be obvious. If you fail to observe the light after several seconds be sure to notify me. It's important to be comfortable with what is expected of you before the experiment starts, so if you have any questions or uncertainties at all, please be sure to voice them. My next command will be 'Mark', whereupon the timed interval will start and you will commence moving the alidade so as to lock on to the target. When you have locked on to the target, quickly reply with 'Mark'. That observation will then be concluded and we will prepare for the next signal. Do you have any questions at this time?"

E. Pilot Study

The Pilot Study had two basic purposes: (1) to provide feedback on experimental sensitivity, and (2) to provide a standard by which to judge the training and performance of inexperienced observers.

Flashtubes operating in the single flick mode appear to "jump" as was described in Section I.A. above. Incandescent sources generally seem to suffer less from this phenomenon. In other words, it is easier to take a bearing on a flashing incandescent source than on a flashing single flick strobe of the same flash repetition rate. It seemed reasonable at the outset to expect similar results from our experimental apparatus. The phenomenon does exist, yet if we could not duplicate it in the lab, then perhaps another experimental approach should be tried.

Any results obtained from the experienced observers would be used as a baseline. We would require the inexperienced observers, after training, to perform approximately as well as the experienced observers.

In the Pilot Study, the basic experimental set up was similar to that already described in Section II.A. above. However, here the observer was required to take bearings on flashtube signals as well as incandescent source signals. Both sources had a flash repetition rate of 4.0 seconds. The incandescent source had a duty cycle of 0.1 seconds while the strobe had a duty cycle of 0.01 seconds. As the original experiment (and Pilot Study) was designed, neither the source nor the observer was in motion. In August 1983, five experienced observers were tested and the results analyzed. There was no statistically discernible difference in performance at the 0.1 level between the strobe and the incandescent source. We had failed to show (through observer performance) the "jump" phenomenon in the lab. Determining that the experiment was not closely enough related to real-world conditions, we decided to place the observer in motion during the tests, hoping to increase the sensitivity of the experiment. This required a basic restart of the effort since the introduction of motion would add to the complexity of the experiment. The effort was restarted in October 1983. Due to their operational commitments, I was unable to re-test the same experienced observers. A new set

was chosen for the re-tests. Time constraints did not allow many repetitions and due to the small sample size, a reliable statistical inference could not be drawn. However, for the re-tests bearing accuracies were about the same, but the amount of time required to obtain the bearing to the strobe source was nearly three times longer than for the incandescent source. Apparently, it was more difficult to take bearings on the strobe source. I was then satisfied that the experimental apparatus was adequate.

F. Flashtube Waveform

It was necessary to gain an understanding of the intensity-time relationship for the single flick flashtube light burst. Not only is the general wave shape of interest, but the total duration is required to determine duty cycles for various multiflick signals.

This information was obtained by optically coupling the HICON stroboscope through an EG&G model 585-66 high-sensitivity detector head (S-10 photomultiplier tube encompassing a spectral range from 200 to 750 nanometers) to a Nicolet Model 4094 digital oscilloscope. Figure 3 provides a simple schematic of the arrangement.

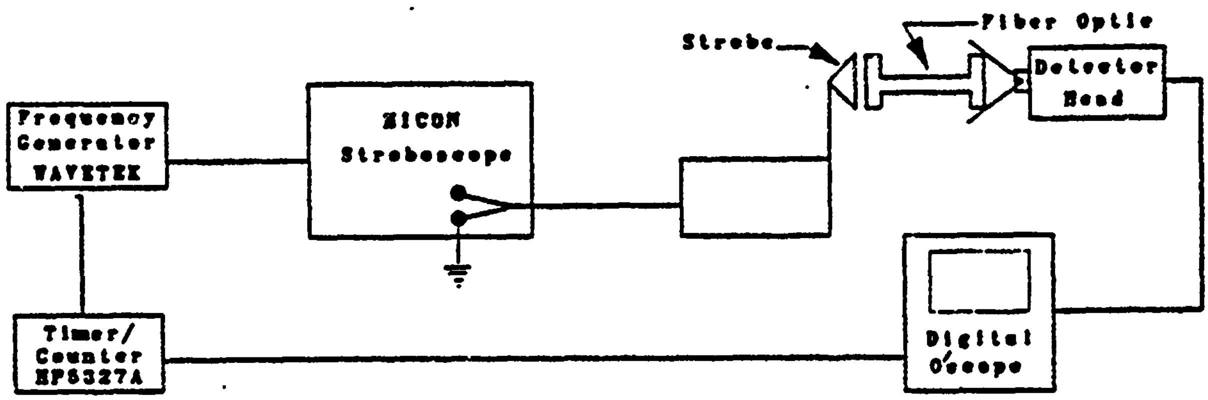

FIGURE 3: OPTICAL COUPLE SCHEMATIC

Figure 4 depicts the intensity-time relationship. The axis of abscissa indicates not only the time in milliseconds, but also the cumulative area under the curve as expressed as a percent of the total area under the curve. Note that 96% of the total light burst energy has occurred in 5 milliseconds, yet there is a miniscule tail at 9 milliseconds. For computational convenience, the pulse length was chosen at 10 milliseconds. As mentioned in Section I.C., for light pulses less than the critical duration (we will accept 100 milliseconds) the actual waveform is basically irrelevant. One is concerned

with the total or integrated light energy available during the flash(es). It would seem that in this case about 10 flicks in rapid sucession (100 HZ) would maximize the total energy below critical duration.

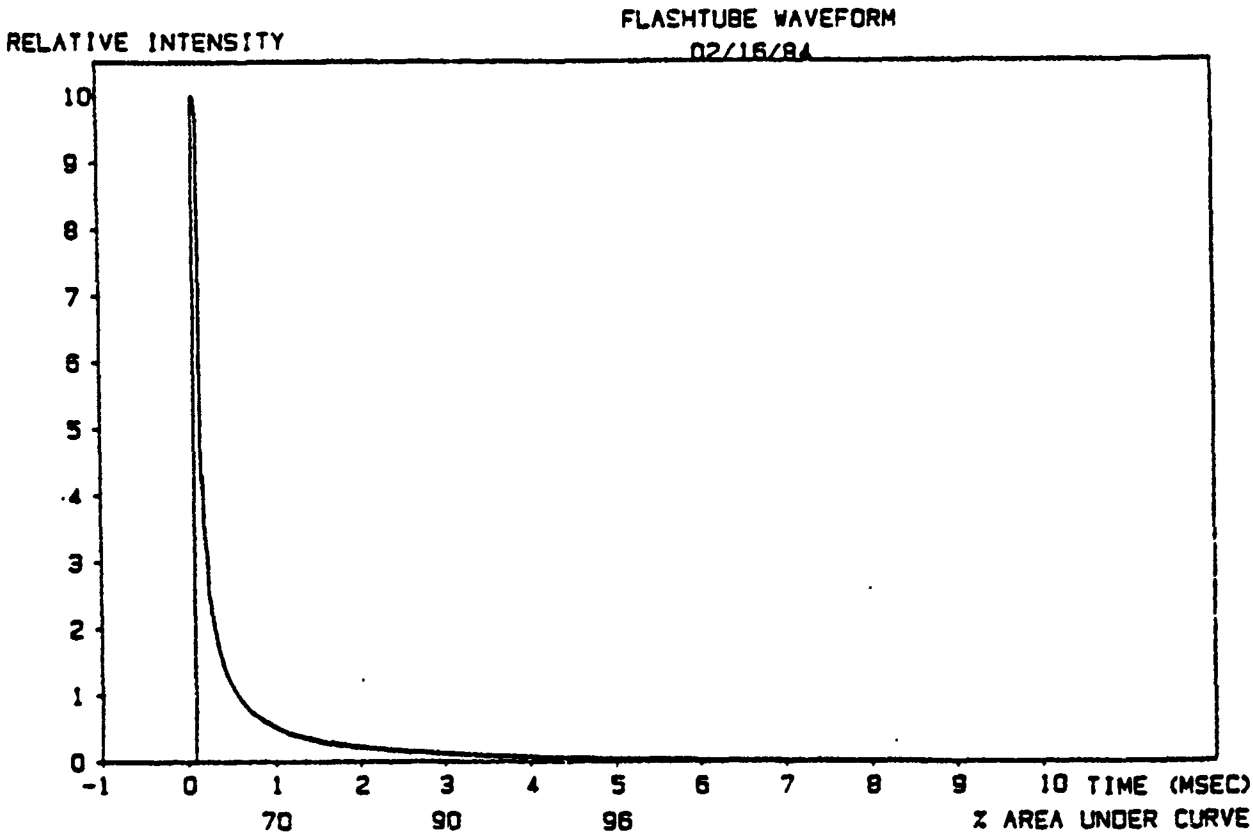

FIGURE 4: TIME-INTENSITY RELATIONSHIP (SINGLE FLICK)

III. RESULTS AND DISCUSSION

A. Preliminary Remarks

The overall performance of an observer is dependent primarily on two variables. He must be reasonably accurate and must perform his task reasonably quickly. Realistically, good navigation information must be timely and accurate. To a marine pilot, a bearing that is exactly correct but requiring 5 minutes of observation is usually of no more value than the rapidly taken bearing that is five degrees in error.

Therefore, it seemed prudent to define observer performance in terms of both the time required to take the bearing and the accuracy of the bearing. In practically all cases, however, the bearing accuracy was within practical tolerable limits (0.5 degrees). The inclusion of the accuracy data adds to our understanding of the overall observer performance trends.

I have defined performance, P, as the product of bearing accuracy (degrees) and elapsed observation time (seconds). Therefore, the lower the value of P, the better the performance. But as expected with response-time experiments of this type, P doesn't have a normal distribution and so a natural logarithm data transformation was carried out. This normal distribution is required for the analysis of variance statistics. Unfortunately, the logarithm of the product of time and bearing accuracy is a little difficult to conceptualize. I have, therefore, also included some analysis of the time data. The time analysis will provide results the reader can easily relate to, such as the effect on lock-on time when the flash repetition rate is increased.

B. General Statistical Discussion

The analysis of variance assumes both normal distributions and equal variances (homoscedasticity). Most reaction time data are not normally distributed and therefore must be transformed to meet this requirement. This experiment was not the exception. Unexpectedly, the variances within the individual observations were not approximately equal. Therefore, in order to correct the above discrepancies the data were transformed, taking care that a realistic model was produced on regression. The normality problem was easily solved, but the homoscedasticity problem was solved to my satisfaction only after several different transformation attempts (i.e., Log P; 1/(P+1)). The unequal variances proved to affect the level of significance in both the main factors and the interactions. From the different transforms attempted, it appeared as though the level of significance of the interactions was reduced as the variances approached approximate equality.

The results of the analysis of variances were:

(1) The main effects (FRR, Flick #, Flick Freq.) were very significant, approaching 0.00.

(2) The positive interaction between frequency and flash repetition rate was highly significant (level of significance = 0.004).

(3) The positive interaction between frequency and number of flicks was highly significant (level of significance = 0.004).

(4) The positive interaction between flash repetition rate and the number of flicks was significant (level of significance = 0.025).

(5) The three-way interaction was not significant.

There is some doubt if the interaction between flash repetition rate and the number of flicks is actually significant, or simply an experimental artifact. This uncertainty is due largely to some inequality of the variances. Much of the variance is attributed to reaction times associated with the data as well as the fact that each observer made only one observation of each of the 42 signals. HAYS states (HAYS, 1973):

> "To a very large extent, the presence or absence of interactions in an experiment is governed by the scale of measurement used for the dependent variable. Thus, in terms of the original scale of measurement interaction may be present, but if, for example, the values are transformed into their respective logarithms, interaction effects may vanish. It is clear that in many circumstances evidence for interaction reflects not so much a state of nature as our own inability to find the proper measurement scales for the phenomena we study."

Since the dependent variable (observer performance) was chosen arbitrarily, it is not unlikely that a transformation exists which would cause the interaction terms to vanish. We did not conduct an exhaustive search for such a transformation and a discussion on these interaction terms and their effects will not be addressed here. The fact that all three main factors were significant means that when discussing the effect of one main factor on observer performance, one must state the levels of the other two main factors. For example, to state the effect on observer performance for a flash repetition rate of 4 seconds, one must specify whether the flick frequency was 10 HZ or 44 HZ and how many flicks were used to compose the signal. As a consequence of having to specify each of the main factors, the experimental goals defined in section I.F. are not easily and clearly attained. A new approach is considered in the next section which simplifies the specification of important flashtube signal parameters.

The model chosen for the regression was:

$$LN(P + 1) = A + BX_1^C + DX_2^E + FX_3^G$$

where: P = Performance

X_1 = Flash Repetition Rate
X_2 = Number of Flicks
X_3 = Flick Frequency

and A, B, C, D, E, F, G, represent constants.

Figures 7, 8, 9 and 10 were generated using this model.

C. Performance Results

As promised in the preceding section, the complexities surrounding the main factors and their effects may now be addressed. These effects may be explained not in terms of the original factors but by a new approach. This new approach will be to consider a new quantity called the multiflick flash length that encompasses these effects. The multiflick flash length is the period of time from the onset of the first flick in the multiflick burst to the cessation of the final flick in the burst. This time period includes the "off" period between individual flicks and is a function of both flick frequency and the number of flicks in the composite flash. The performance can be modelled (similar to the previous section) in terms of flash repetition rate and the multiflick flash length:

$$LN\ (P+1) = A + BX_1^C + DX_2^E$$

where X_1 = flash repetition rate
X_2 = multiflick flash length

and A, B, C, D, E = constants

Such a model yields essentially the same performance results as the 3-factor model used in the previous section. For signals well above observer threshold, the specification of the multiflick flash length (instead of flick frequency and number of flicks) seems intuitively desirable because:

(1) The performance results are essentially the same.

(2) The multiflick flash length is a function of both the flick frequency and the number of flicks in the composite flash.

(3) It is convenient to deal with two independent variables instead of the original three.

(4) Above a certain frequency where the light appears steady, the eye cannot distinguish different frequencies anyway.

It should be emphasized, however, that in dealing with the actual visual range (and thus threshold) of a strobe source, the total energy contained within the signal becomes important and one must consider both the flick frequency and the number of flicks in the composite flash.

Except for the flash repetition rate, the multiflick flash length is probably the most important parameter to specify when describing a suprathreshold multiflick flashtube signal. The multiflick flash length appears to reasonably account for the effects of flick frequency and number of flicks in the multiflick flash. For example, observer performance is better for a 3-flick, 11 HZ signal than for a 3-flick, 44 HZ signal. The former signal has a much longer multiflick flash length and the observer performance is better. The unequal observer performance for the two signals was predicted by their different flash lengths. Alternately, a 32-flick, 44 HZ signal and an 8-flick, 11 HZ signal, which are approximately equal in multiflick flash lengths, are reasonably close in observer performance. Figure 5 demonstrates

two composite flashes of about equal multiflick flash length. Both multiflick flashes (well above visual threshold) are perceived by the human observer as a single, uninterrupted burst of light. However, it is clear from the figure, that the two signals are considerably different in composition, including the amount of energy contained in the flash. The 44 HZ signal appears to enjoy a slight performance advantage but this is probably due to the increased energy available in that signal. Figure 6 describes observer lock-on time as a function of the multiflick flash length for the three flash repetition rates tested and indicates how long it will take an observer to lock-on to a flashing strobe for the flash rate tested. Note there is little practical difference between the 1-second and 2-second flash repetition rates for multiflick flash lengths beyond 0.6 seconds and little practical gain beyond about 1.6 seconds for the 4-second flash repetition rate. Based on this plot, the multiflick flash length should probably be between 0.6 and 1.6 seconds. This is a somewhat narrower window than what can be interpretted from White's data (White, 1965).

Figure 7 indicates how performance decreases as the time between flashes is increased for the 44 HZ data. The seven curves represent those signals having 1-flick, 3-flicks, 5-flicks, 8-flicks, 16-flicks, 32-flicks, and 64-flicks.

Figure 8 demonstrates, for the 10 HZ data, how observer performance gets better as the number of flicks in the multiflick flash is increased. As one might expect, those signals which are flashed more often (e.g., flash repetition rate = 1) have a better performance for the same number of flicks. Figure 9 describes this effect for the 44 HZ data.

Figure 10 provides some interesting results but requires careful explanation. The graphs portray observer's performance for various signals as the time between flashes is increased. The upper curve (frequency = 44 HZ; number of flicks = 1) represents a "worst case" signal. The lowest curve (frequency = 44 HZ; number of flicks = 64) represents a "best case" signal (practically a steady light). Inside this performance envelope, are plotted two signals of entirely different frequency and flick composition but whose multiflick flash lengths are essentially the same. The two signals of the same multiflick flash are reasonably close in observer performance, though the higher energy 44 HZ signal appears to have a modest advantage.

We now have two parameters to specify for the optimum flashtube signal. We should specify the flash repetition rate and we should specify the multiflick flash length.

The flick frequency and the time duration of each individual flick must be given some consideration in specifying the multiflick flash length. For flashes of approximately equal energy, observers cannot distinguish any difference in flash lengths less than about 0.1 seconds in duration (due to visual persistence). In other words, a flick that is 0.001 seconds in duration may appear of the same length as one of 0.1 seconds in duration. The work reported here did not address variation in individual flick length. However, based on the energy integration time of Bloch's Law (less than about 0.1 seconds), and the concept of visual persistence, it appears that any flick length below about 0.1 seconds is acceptable. However, a 0.01 second flick (used in this experiment), has the advantage of being electronically easily

obtained and represents the ability to use higher frequencies and therefore more flicks and more energy and consequently more range for the signal light. The flick frequency should be such that the proper multiflick flash length can be obtained without the observer being able to distinguish individual flicks. Within this limitation, one has the freedom to construct many possible "equal" (in terms of suprathreshold observer performance at some fixed distance) signals. For example, at some distance, the observer performance is the same for both 32-flick, 44 HZ signal and an 8-flick, 10 HZ signal. Both sources are well above threshold at this distance. However, as the distance from the sources is increased even further, the lower energy signal (10 HZ, here) will eventually drop below threshold and be lost while the higher energy signal (44 HZ) is still visible and useful as an aid to navigation. It is here that one may employ energy efficient methods to obtain an acceptable signal for the least outlay of energy at some particular distance or range of interest. For example, one of the reasonably good signals (in terms of observer performance) we tested was comprised of eight flicks, each flick of 0.01 seconds in duration and at a flick frequency of 10 HZ. This signal has a multiflick flash length of 0.8 seconds and the dark adapted observer cannot distinguish the indivdual flicks. Figure 5 indicates that for a 4-second flash repetition rate, the observer will require about 18 seconds to lock-on and for a 2-second flash repetition rate, the observer will require about 11 seconds to lock-on.

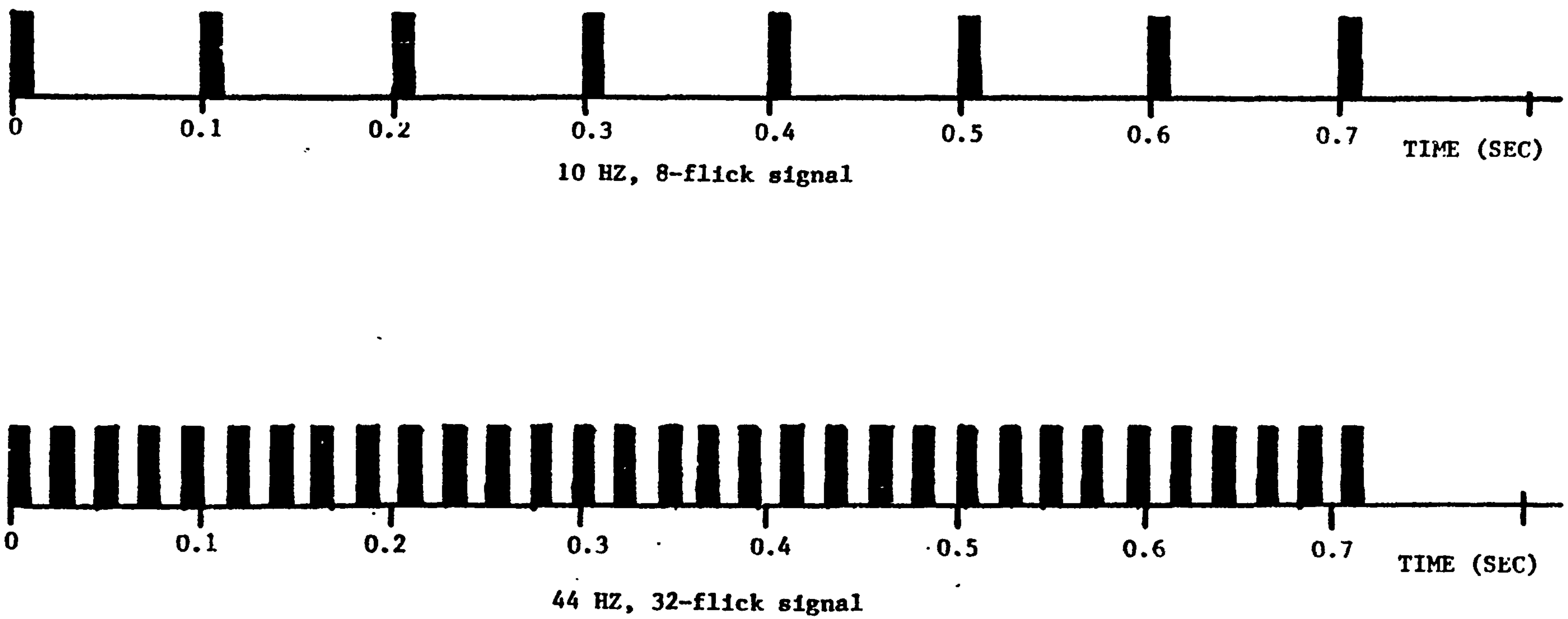

FIGURE 5: PICTORIAL REPRESENTATION OF TWO DIFFERENT MULTIFLICK FLASHES

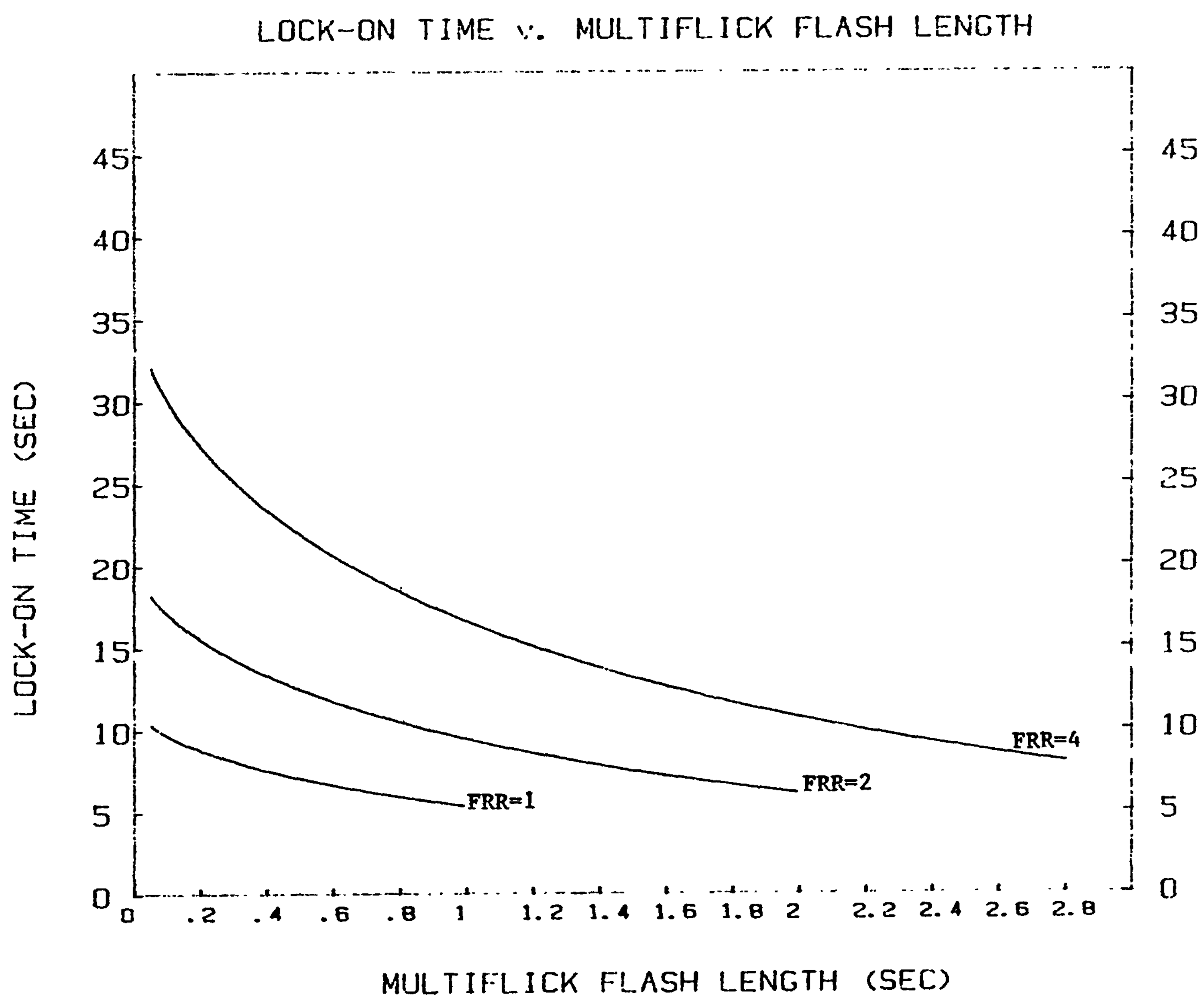

FIGURE 6. TIME REQUIRED TO TAKE A BEARING FOR THE VARIOUS FLASH REPETITION RATES

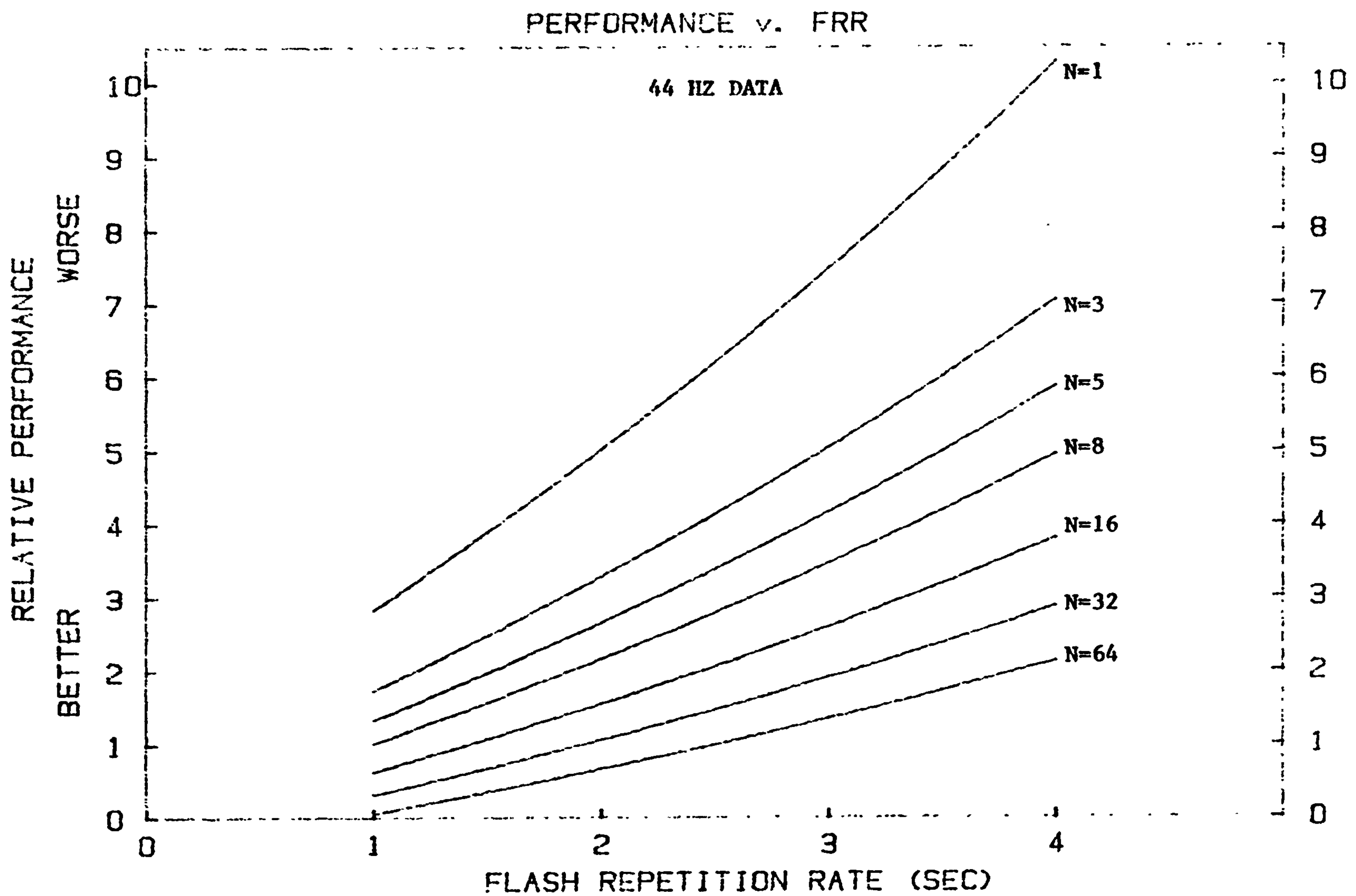

FIGURE 7. PERFORMANCE GETS WORSE AS THE TIME BETWEEN FLASHES INCREASES

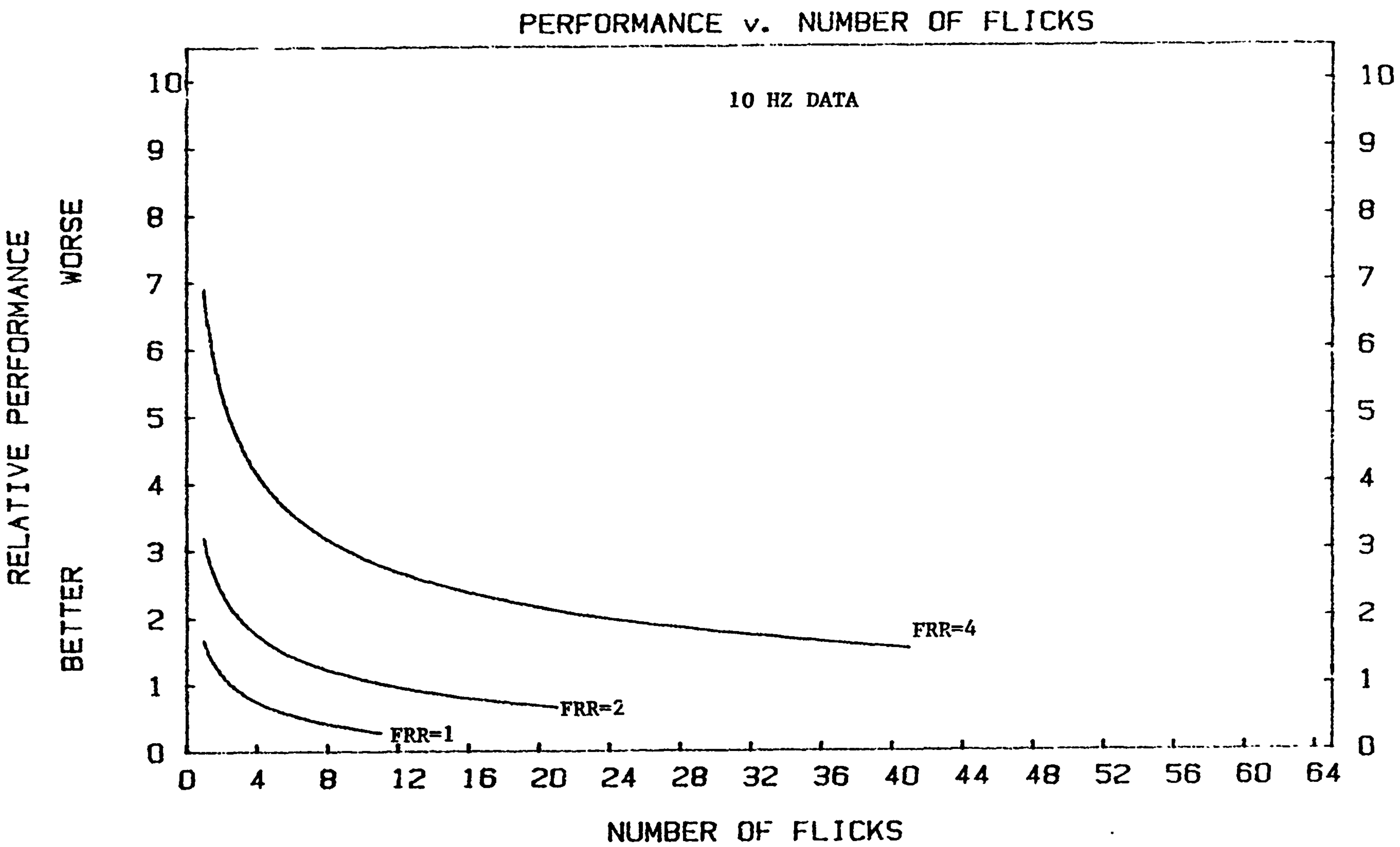

FIGURE 8. PERFORMANCE GETS BETTER AS THE NUMBER OF FLICKS IN THE COMPOSITE FLASH IS INCREASED (10 HZ DATA).

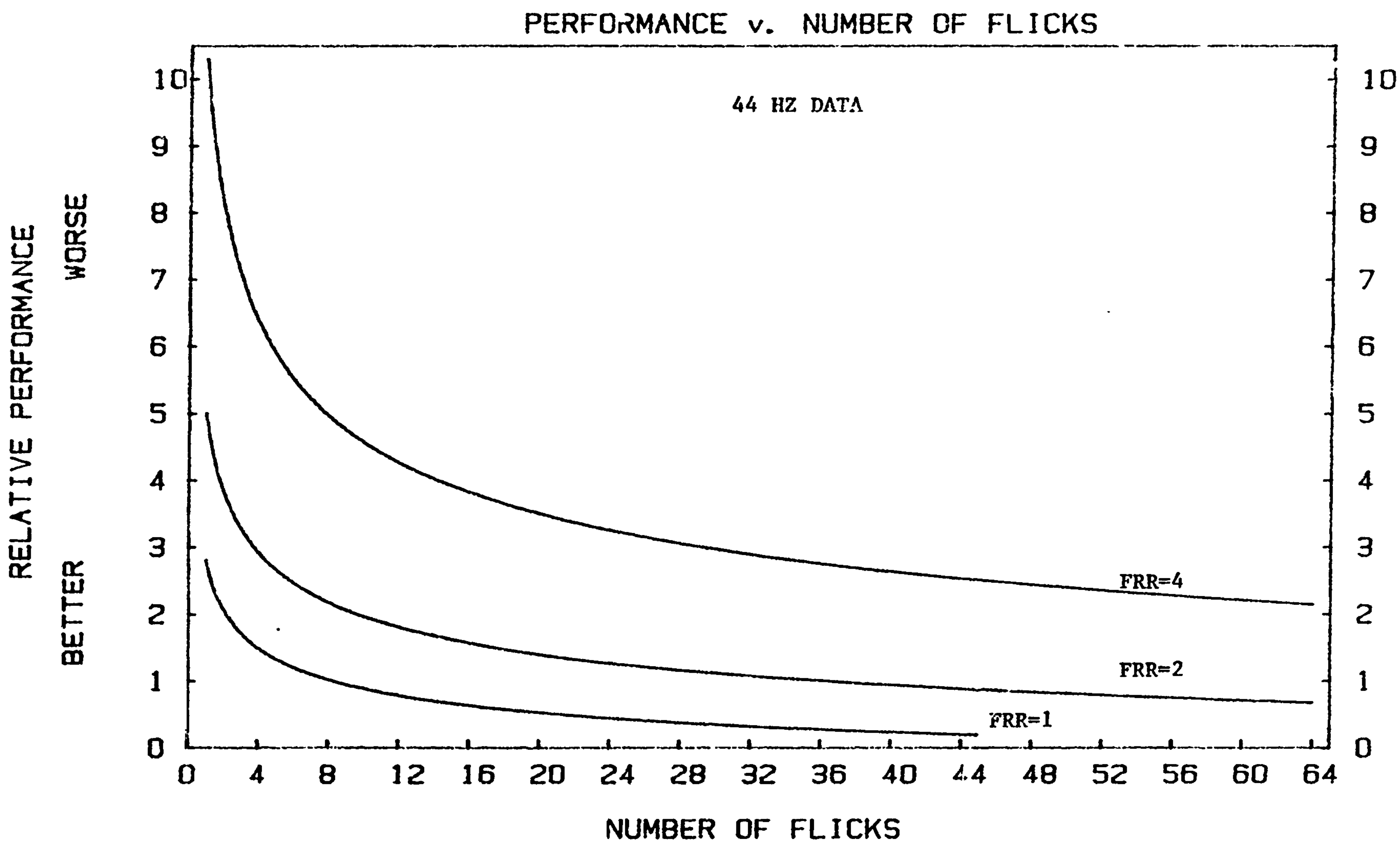

FIGURE 9. PERFORMANCE GETS BETTER AS THE NUMBER OF FLICKS IN THE COMPOSITE FLASH IS INCREASED (44 HZ DATA).

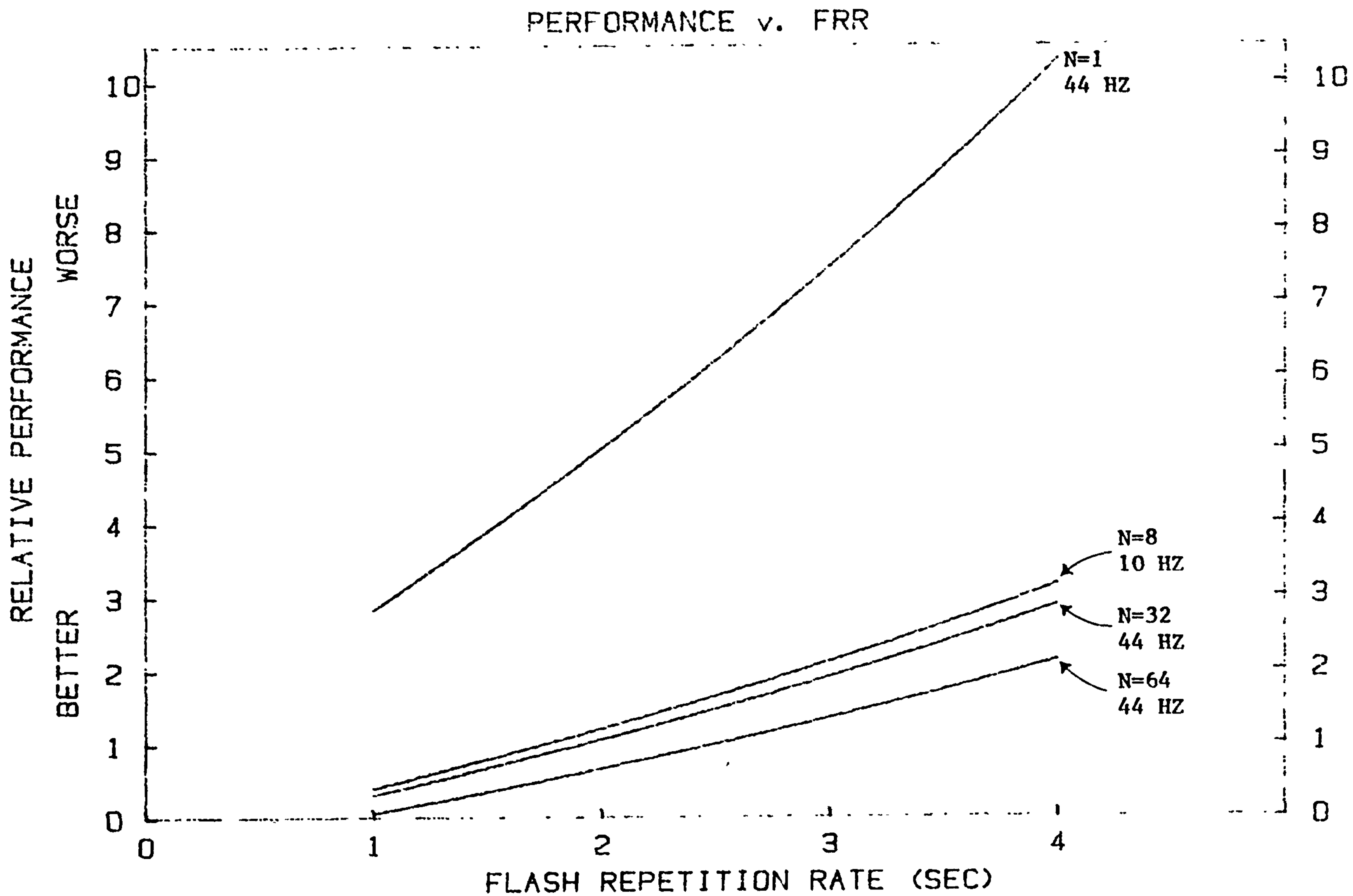

FIGURE 10. PERFORMANCE "ENVELOPE" WITH TWO SIGNALS OF ABOUT THE SAME MULTIFLICK FLASHLENGTH.

IV. CONCLUSIONS AND RECOMMENDATIONS

The conclusions are as follows:

(1) The two parameters necessary to adequately specify the optimum suprathreshold flashtube signal in terms of observer performance, are flash repetition rate and multiflick flash length.

(2) The multiflick flash length should be between 0.6 seconds and about 1.6 seconds in duration.

(3) Each individual flick should be less than 0.1 seconds in duration. A much shorter flick duration (for example, 0.01 seconds) will allow greater flexibility in selecting an appropriate flick frequency for the composite flash.

The recommendations are as follows:

(1) Since observer performance was practically the same for the 1-second and 2-second flash repetition rates, it is recommended that a 2-second flash repetition rate (flash length greater than 0.6 seconds) be used in lieu of the 1-second flash repetition rate signal (except where the higher conspicuity of the 1-second signal is deemed desirable). As detailed in the previous section, there is considerable latitude available in choosing the desired flick frequency and number of flicks to arrive at the proper multiflick flash length. Here, one must bargain between energy and (visibility) range of the signal. The more energy the signal puts out in terms of flick frequency and number of flicks, the longer its range. We must develop a method to relate individual flick length and number of flicks to signal energy consumption and then determine if there is some optimum combination of flicks and flick length from an energy efficiency point of view. We must also have an accurate theoretical means to calculate the range of multiflick signals. There is much in the literature on the fixed equivalent intensity for a single flash of light but there is little in the literature on how to compute the equivalent fixed intensity of multiflick flashes.

(2) It is recommended that further study be carried out to attempt to quantify the precise relationship between multiflick flashes and their equivalent fixed intensity. The calculated equivalent fixed intensities could then be inserted into Allard's Law to yield appropriate signal ranges.

(3) It is also recommended that further study be conducted to determine the optimum mix of flick length and number of flicks from an energy efficiency point of view. One may then select the most energy efficient composite flashes and determine their nominal visible ranges to arrive at optimal signals for various marine locations.

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